

WEAKLY SELF-INTERACTING DARK MATTER AND THE STRUCTURE OF DARK HALOS

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ABSTRACT

We study the formation of dark halos in a Λ CDM universe under the assumption that Cold Dark Matter particles have a finite cross-section for elastic collisions. We compare evolution when CDM mean free paths are comparable to halo sizes with the collisionless and fluid limits. We show that a few collisions per particle per Hubble time at halo centre can substantially affect the central density profile. Cross-sections an order of magnitude larger produce sufficient relaxation for rich clusters to develop core radii in the range 100-200 h^{-1} kpc. The structural evolution of halos is a competition between collisional relaxation caused by individual particle interactions and violent relaxation resulting from the infall and merging processes by which clusters grow. Although our simulations concentrate on systems of cluster size, we can scale our results to address the halo structure expected for dwarf galaxies. We find that collision cross-sections sufficiently large to significantly modify the cores of such galaxies produce cluster cores which are too large and/or too round to be consistent with observation. Thus the simplest model for self-interacting dark matter is unable to improve fits to published dwarf galaxy rotation curves without violating other observational constraints.

Subject headings: dark-matter-galaxies:formation-methods:numerical

1. INTRODUCTION

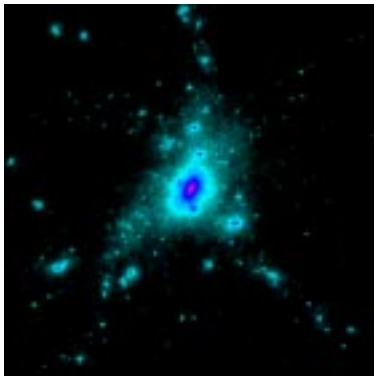
Recent measurements of structure in the microwave background radiation (Lange et al. 2000; Hanany et al. 2000), although eliminating the “concordance” model (Bahcall et al. 1999), provide strong support for the general theoretical paradigm on which this model was based. Such Cold Dark Matter (CDM) universes are in excellent agreement with observed large-scale structure, but may be inconsistent with the observed structure of *nonlinear* dark matter dominated systems. Navarro, Frenk & White (1997, NFW hereafter) claimed that the density profiles of virialized CDM halos are reasonably approximated by a “universal” form with singular behavior near its center. More recent simulations with higher resolution have confirmed this result, suggesting that the central cusps may be even steeper than the NFW profile (Moore et al. 1999b; Klypin et al. 1999, see also Jing & Suto 2000). Such structures appear inconsistent with published data on the rotation curves of dwarf galaxies (Moore 1994; Flores and Primack 1994) although this inconsistency may reflect limitations of the data rather than of the theory (van den Bosch et al. 1999; van den Bosch & Swaters 2000). There may also be a discrepancy between the rich substructure seen in simulations of CDM halos and the relatively small number of satellite galaxies observed in the Milky Way’s halo (Moore et al. 1999a; Klypin et al. 1999).

Spergel & Steinhardt (2000) suggested that a finite cross-section for elastic collisions, such that the mean free path of CDM particles is short in halo cores but long in their outer parts, might alleviate these difficulties. Their

proposal has attracted considerable attention. Ostriker (2000) argued that the massive black holes could grow naturally at the centers of galactic spheroids through the accretion of such dark matter. Miralda-Escudé (2000) pointed out that collisional dark matter might produce galaxy clusters which are rounder than observed. Mo & Mao (2000) and Firmani et al. (2000) investigated how self-interacting dark matter might effect galaxy rotation curves. Hogan & Dalcanton (2000) considered how the structural properties of halos might scale with their mass. Burkert (2000) and Kochanek & White (2000) studied how collisional relaxation would affect the structure of isolated equilibrium halos, while Moore et al. (2000) and Yoshida et al. (2000) simulated cluster evolution in a cosmologically realistic context but in the fluid limit (very short mean free path). In this limit collisional dark matter produces more cuspy profiles than collisionless CDM, and so gives even poorer fits to published rotation curves for dwarf galaxies.

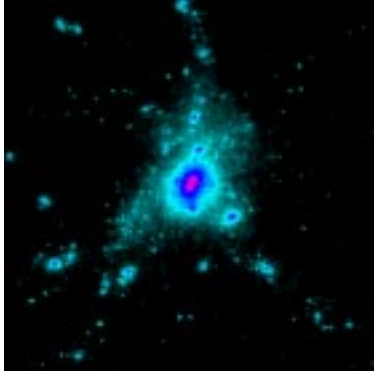
In this *Letter* we continue exploring how collisions affect the structure of dark halos. We simulate the formation of a massive halo in a Λ CDM universe assuming scattering cross-sections varying over a wide range. The inclusion of the infall and merging which occur when halos are embedded in their proper cosmological context leads to core evolution which is considerably more complex than the expansion followed by collapse seen in the simulations of Burkert(2000) and Kochanek & White(2000). Cross-sections which would significantly modify the core structure of dwarf galaxies produce galaxy cluster cores which are inconsistent with observation.

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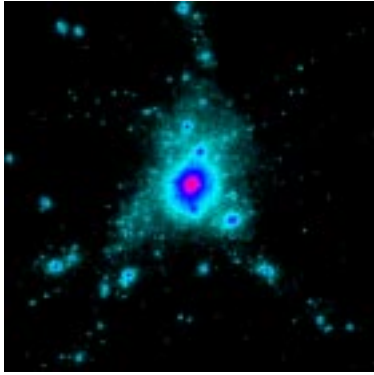
S1

1 : 0.82 : 0.65



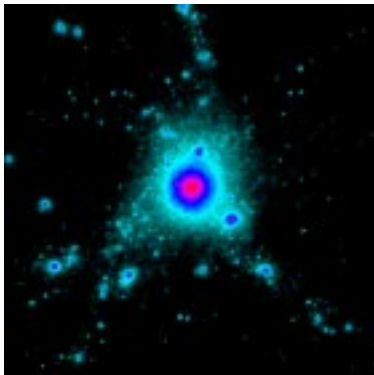
S1Wa

$\sigma^* = 0.1 \text{ cm}^2 \text{ g}^{-1}$
 $r_c = 40 \text{ } h^{-1} \text{ kpc}$
 1 : 0.88 : 0.66



S1Wb

$\sigma^* = 1.0 \text{ cm}^2 \text{ g}^{-1}$
 $r_c = 100 \text{ } h^{-1} \text{ kpc}$
 1 : 0.91 : 0.72



S1Wc

$\sigma^* = 10.0 \text{ cm}^2 \text{ g}^{-1}$
 $r_c = 160 \text{ } h^{-1} \text{ kpc}$
 1 : 0.98 : 0.89

FIG. 1.— Projected mass distributions in a box $15h^{-1}\text{Mpc}$ on a side. The axial ratios, core radii and collision cross-sections per unit mass are given for each model to the right of the corresponding image.

2. THE SIMULATIONS

Our simulations use the parallel tree code GADGET developed by Springel (1999, see also Springel, Yoshida & White 2000). We study the same cluster as Yoshida et al. (2000) who resimulated the second most massive ob-

ject in the ΛCDM simulation of Kauffmann et al. (1999). In order to simulate elastic scattering of CDM particles we adopt the Monte Carlo method introduced by Burkert (2000). We implement this scheme in the following manner. At each time step we evaluate the scattering probability for particle i ,

$$P = \rho_i \sigma^* V_{\text{rel}} \Delta t, \quad (1)$$

where ρ_i is the local density at the particle's position, σ^* is the scattering cross-section per unit mass, $V_{\text{rel}} = |\mathbf{v}_i - \mathbf{v}_{\text{ngb}}|$ is the relative velocity between the particle and its nearest neighbour, and Δt is the time step. This prescription is similar to Burkert's, but uses the relative velocity rather than the absolute velocity of particle i . Kochanek & White (2000) use a similar scheme but estimate the scattering rate more accurately by looping over a certain number of neighbours. However, the larger smoothing involved in such a procedure can itself introduce difficulties in regions with significant velocity gradients (Meiburg 1986), and so we prefer our simpler scheme which should be unbiased even if somewhat noisier. We choose timesteps small enough to ensure that a particle travels only a minor fraction of its mean free path within Δt . We assume each collision to be elastic, of hard-sphere type, and to have a cross-section independent of velocity. Scattering is assumed isotropic in the center-of-mass frame, so that relative velocities are randomly reoriented in each collision. We carry out simulations for three values of σ^* differing by factors of ten.

Most of our simulations employ 0.5×10^6 particles in the high resolution region, with a mass per particle $m_p = 0.68 \times 10^{10} h^{-1} M_\odot$. The gravitational softening length is set to $20h^{-1}\text{kpc}$, which is $\sim 1.4\%$ of the virial radius of the final cluster. We ran one simulation with 5 times better mass resolution and 7 times better spatial resolution to check for numerical convergence. All of our resimulations start from the same initial conditions. The background cosmology is flat with matter density $\Omega_m = 0.3$, cosmological constant $\Omega_\Lambda = 0.7$ and expansion rate $H_0 = 70 \text{ km}^{-1}\text{Mpc}^{-1}$. It has a CDM power spectrum normalised so that $\sigma_8 = 0.9$. The virial mass of the final cluster is $M_{200} = 7.4 \times 10^{14} h^{-1} M_\odot$, determined as the mass within the radius $R_{200} = 1.46h^{-1}\text{Mpc}$ where the enclosed mean overdensity is 200 times the critical value.

3. RESULTS

The large-scale matter distribution in all our simulations looks very similar. Because we start from identical initial conditions, the particle distributions differ only in regions where collisions are important. Figure 1 shows that the final cluster is more nearly spherical and has a larger core radius for larger collision cross-section. The quoted axial ratios are determined from the inertia tensors of the matter at densities exceeding 100 times the critical value. Miralda-Escude (2000) argues that the ellipticity of cluster cores, as inferred from gravitational lensing observations, can be used to limit the interaction cross-section. Among our final clusters, S1W-b and S1W-c are severely constrained by the limits he quotes.

In Figure 2 we show density profiles for all of our simulations. Also plotted in the bottom panel is the mean collision number per particle. (We counted collisions for

each particle throughout the simulation.) Figure 2 clearly shows the presence of a core whose extent depends on the cross-section. For our intermediate cross-section case (S1W-b), we also carried out a higher resolution simulation. The two density profiles agree very well (see Figure 2) showing that our simulations have converged numerically on scales larger than the gravitational softening length. The mean collision count at cluster center is 3 for S1W-a, 8 for S1W-b, and 35 for S1W-c. Thus only a few collisions per particle in a Hubble time suffice to affect the central density profile, and about 10 collisions per particle result in a core with $r_c \geq 100h^{-1}\text{kpc}$. (We define the core radius as the point where the density profile becomes steeper than $\propto r^{-1}$. Core radii by this definition are given on the right of Figure 1.)

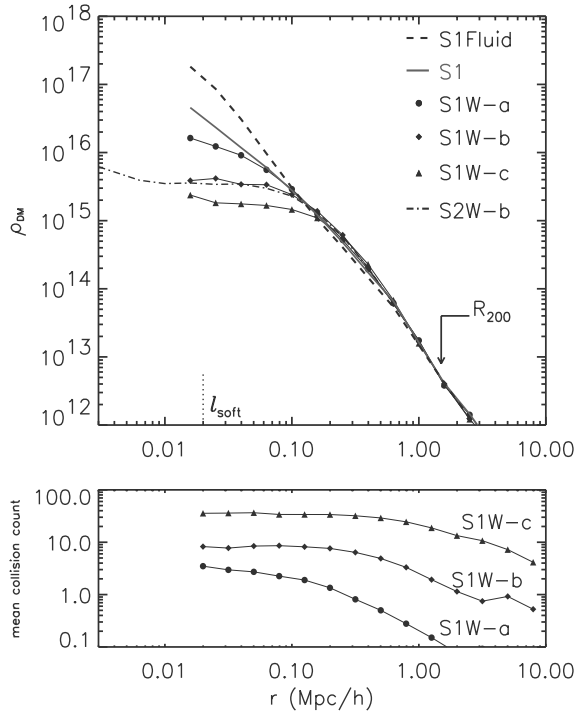


FIG. 2.— Density profiles (top) and mean collision counts per particle (bottom). The vertical dotted line in the top panel indicates the gravitational softening length of our S1 simulations. The virial radius R_{200} of the final cluster is shown as an arrow. The “fluid” dark matter case from Yoshida et al. (2000) is plotted as the dashed line, while the dash-dotted line represents our higher resolution simulation of the medium cross-section case (S2W-b).

Unlike an isolated system, our cluster grows through successive mergers. Thus the material in its central region is a mixture of the material from a number of its progenitors. Figure 3, a time sequence of density profiles for our S1W-c simulation, shows clearly how merger events interrupt the core evolution and produce low density cores. We let this simulation run beyond the present time to $a=1.72$, where a is the expansion parameter normalised to its present value. During the time interval plotted, the cluster experiences major mergers at $a \sim 0.75$ and $a \sim 1.4$. Each of these events is associated with an increase of the core radius. Subsequent relaxation causes the core to shrink again and the central density to rise. For this relatively large cross-section, relaxation-driven core expansion does not occur within the time interval shown. In contrast to this complex behavior, the virial mass of

the cluster grows quite smoothly, approximately doubling between $a = 0.73$ and $a = 1.72$. Clearly, the core radius of the cluster at $a = 1$ results from an interplay between collisional relaxation driven by particle collisions and violent relaxation caused by mergers.

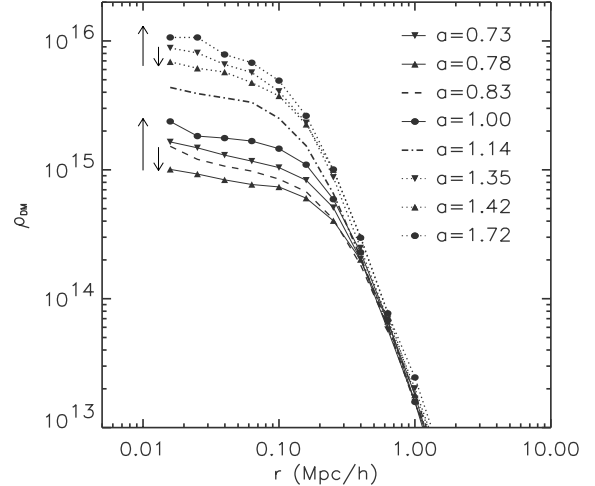


FIG. 3.— We plot the time evolution of the density profile in S1W-c (the largest cross-section case). Time is indicated by the expansion parameter a . The series starts at $a = 0.73$ just before the final merger occurs. After the merger the core settles down again by $a = 0.78$ and then enters a core-collapse phase which is interrupted by another major merger at $a = 1.4$.

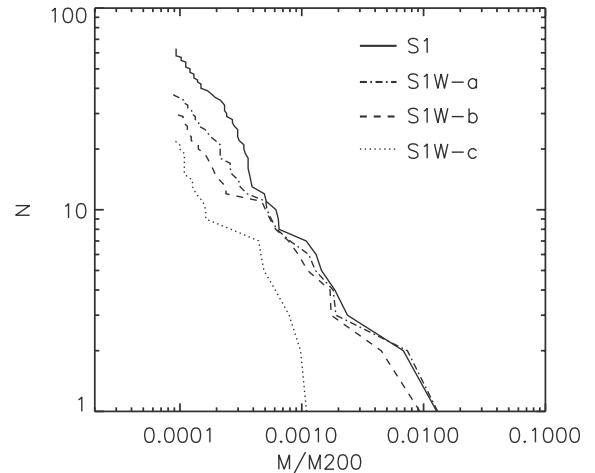


FIG. 4.— The total number of subhalos within R_{200} is plotted as a function of the lower limit to their mass in units of M_{200} . Results are plotted for halos containing 10 or more particles.

In Figure 4 we compare the amount of substructure within R_{200} in our various simulations. We use the SUBFIND algorithm by Springel (1999) to identify subhalos in the final cluster. This identifies gravitationally self-bound sets of particles that are at higher density than the smooth background of cluster material. Local density is defined at each particle’s position in a SPH fashion. Using this procedure we find that 3.7%, 3.6%, 2.5%, and 0.7% of the cluster mass is included in subhalos in S1, S1W-a, S1W-b and S1W-c respectively. Although low mass substructures are somewhat less abundant for larger cross-sections, massive subhalos are *not* substantially disrupted in S1W-a and S1W-b. Many of the massive subhalos are $\sim 1h^{-1}\text{Mpc}$ from the cluster center, where particle collisions are rare

in these models (see the bottom panel of Figure 2). Hence “dark matter evaporation” (Spergel & Steinhardt 2000) is ineffective for them. On the other hand, the massive sub-halos in S1W-c are totally disrupted. Infalling halos are rapidly stripped by collisions with “diffuse” cluster dark matter in this case.

4. SUMMARY AND DISCUSSION

By simulating weakly collisional particle systems, we have studied the formation of a cluster halo in a Λ CDM universe made of self-interacting dark matter. To make contact with observations of the rotation curves of dark matter dominated dwarf galaxies, we can scale our results as follows.

The number of collisions in the core of a halo over a Hubble time (t_H) can be estimated as

$$N_{\text{coll}} = \rho \sigma^* V t_H. \quad (2)$$

The characteristic density here can be defined as $\rho \equiv M_s/r_s^3$ and the velocity as $V \equiv \sqrt{GM_s/r_s}$, where r_s is the characteristic scale of an NFW fit to the halo density profile and M_s is the mass enclosed within r_s . Then

$$N_{\text{coll}} \propto M_s^{3/2} \sigma^* r_s^{-7/2} t_H. \quad (3)$$

We assume the cross-section per unit mass, σ^* , to be independent of collision velocity and concentrate on halos with the structure expected in a Λ CDM universe. In this cosmology and in the absence of collisional effects a halo of mass $\sim 10^{10} M_\odot$ is predicted to have virial radius $r_{200} \sim 50 h^{-1} \text{kpc}$, concentration $c = r_{200}/r_s \sim 20$, and maximum circular velocity $V_c \sim 50 \text{ km/s}$. Thus $r_{\text{sd}} = 2.5 h^{-1} \text{kpc}$ and $M_{\text{sd}} = 10^9 h^{-1} M_\odot$. For our cluster, which has concentration $c=12$, we obtain $r_s = 100 h^{-1} \text{kpc}$ and $M_s = 10^{14} h^{-1} M_\odot$. From equation (3) it is clear that a halo of 40 times smaller radius and 10^5 times smaller mass will experience 80 times fewer collisions per particle at r_s . The profile modification caused by collisions in our model S1W-a is close to the minimum which would significantly alter the rotation curves predicted for dwarf galaxies. Thus if the apparent cores in observed systems were a result of such weak collisions, the density profiles of

rich clusters would show cores similar to that seen in our model S1W-c, i.e. $r_c \sim 150 h^{-1} \text{kpc}$. Such large cores are not consistent with the mass distributions inferred from the presence of giant arcs in clusters. Analyses by a number of authors (Kneib et al. 1993; Luppino et al. 1993; Bonnet et al. 1994; Tyson et al. 1998) require core radii in the range $35\text{--}100 h^{-1} \text{kpc}$, typically a factor of two below the value we estimate. These upper limits are actually conservative, since the observed thinness of giant arcs requires substantially smaller cores (Miralda-Escude 1995). In addition, such large cross-sections produce cluster cores too round to be consistent with weak lensing observations as interpreted by Miralda-Escude (2000).

A possible solution might seem to be a cross-section about two orders of magnitude larger than in S1W-c. Dwarf galaxy haloes would then look similar to a scaled version of S1W-c, with a core radius of about $4 h^{-1} \text{kpc}$ for the parameters considered above, while rich clusters would be highly collisional and might have profiles approaching that in our “fluid” simulation. Our earlier work confirmed, however, that such clusters would be almost spherical and so can be excluded following Miralda-Escude’s (2000) argument.

A different resolution might be to introduce an interaction law which implies an energy dependent cross-section such that scattering is less effective in high velocity encounters. This would reduce the difference between cluster and dwarf galaxy halos. This idea requires a more detailed physical model for the dark matter, and we do not pursue it further here. We note that $\sigma^* \propto V^{-1}$ is required to make the collision rate at r_s approximately independent of halo mass.

In summary our results suggest that collisional dark matter cannot produce core radii in dwarf galaxy halos as large as those inferred from rotation curve observations without simultaneously producing cluster cores which are too large and too round to be consistent with gravitational lensing data.

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